Modular Power Standard for Space Explorations Missions

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Future human space exploration will most likely be composed of assemblies of multiple modular spacecraft elements with interconnected electrical power systems. An electrical system composed of a standardized set modular building blocks provides significant development, integration, and operational cost advantages. The modular approach can also provide the flexibility to configure power systems to meet the mission needs. A primary goal of the Advanced Exploration Systems (AES) Modular Power System (AMPS) project is to establish a Modular Power Standard that is needed to realize these benefits. This paper is intended to give the space exploration community a "first look" at the evolving Modular Power Standard and invite their comments and technical contributions.

I. Introduction

THIS paper is intended to explain key elements and overall design philosophy of the evolving Modular Power Standard. Modularity provides a number of advantages over the common practice of designing a power system tailored to the needs of a specific spacecraft. The modular approach can enable a wide array of differing spacecraft power system architectures created from a basic set of building blocks. The flexibility of the approach can be applied across multiple spacecraft. For human exploration the common modular blocks allow the mission to utilize a common set of spares which, in turn, simplifies logistics and improves the supportability of the mission.[1, 2]

A common modular power architecture also allows modular power elements to be moved from one part of the system to another to meet changing mission needs or to respond to contingency situations. It is particularly important for human exploration where missions are long and where capacity for spares is scarce. The modular approach is expected to provide cost savings in the development, integration and operational phases of an exploration program.

The modular power approach requires a thoroughly pre-engineered and tested set of interface standards. To be effective, modular building blocks must be thoroughly defined and characterized to the extent possible while still allowing the flexibility to incorporate new technologies that can improve performance, reliability, and reduce mass. The Modular Power Standard defines a "modular design philosophy" that in turn is applied to all major functions and interfaces throughout a modular power architecture. The AMPS project is developing a set of proposed unit level standards that will provide useful guidance for modular hardware developers but not needlessly constrain technology options, or limit future growth in capability.

This standard goes beyond the unit level modules or Orbital Replacement Units (ORU) as defined by the International Space Station. Often traditional assembly level units of fixed size rarely match the system needs and often result in unused capacity. For this reason, instead of a common unit, a family of units of varied size and capacity are developed. This tends to result in a mixed set of flight spares that are not interchangeable and drive up the mass of logistics spares.

The Modular Power Standard extends modularity down to the subassembly level where individual circuit cards, for example, are modularized as encapsulated replaceable units. The standardization of subassembly level hardware allows designers to scale assembly level functions to specific needs without constraining them to fixed sizes at the unit level.

Examining the weight breakdown of avionics and power units on the International Space Station (ISS) reveals that the external enclosures tends to make up roughly 40% to 60% of the total ORU mass. There is an opportunity to reduce the unused capacity and eliminate surplus mass of by modularizing at the sub assembly level.[1, 2]

The Modular Power Standard must define and characterize all the interfaces that affect the design of the modules. Therefore, the Modular Power Standard includes electrical, data system interfaces, and mechanical interfaces. To maximize the flexibility and scalability benefits of the modular approach the standard must define functions and interfaces so they are easy to service, integrate and configure with a minimum crew time and equipment resources.

There are also less tangible interfaces such as in-space operations and crew safety requirements. The modular power standards define "supportability" requirements to assure that they are readily accessible and replaceable with

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minimum disruption of ongoing mission operations.[4] Modular Standards should also anticipate that missions will involve humans assisted with robotic servicing units.

The Modular Power Standard is, in effect, a convergence of many existing standards from the spacecraft and space power community. For electrical interfaces spacecraft power quality and grounding specs apply. For data system interfaces a number of international interoperability standards for command and data transmission apply. Modular Power will also utilize network standards that define automated network integration and configuration sometimes known as "Plug and Play" standards.[3] Mechanical interfaces, including structural and thermal interfaces, will employ NASA standards to assure that the modules survive structural dynamic environment and space thermal environments while still meeting the supportability requirements.

To contain the scope of the Modular Power Standard discussion in this paper, the focus is on power distribution and management aspect of spacecraft power. To provide an example of a modular unit, this paper describes a Modular Power Distribution Unit or Modular PDU. Discussion of the Modular PDU captures the modular power design philosophy and the major attributes and capabilities of modular power.

II. Modular Power Design Philosophy

A. Modular Approach: Common Building Blocks

The key aspect to the Modular Power Design Philosophy is the concept that a power system can be reduced to a set of functional blocks or assembly level units. These decompose further into sub-assembly level functional blocks that are commonly used throughout the system. The premise is that these lower level functional blocks *can be modularized as building blocks* that can be used to construct an operational power system. These blocks are packaged as individual encapsulated modules with their own physical shell that provides protection for the internal components while providing structural support and thermal conduction for heat removal. The physical form factor for specific modules and the external interfaces are to be standardized and common for all modules of that type or function. The internal module details are not explicitly specified but instead modular standard defines the required functions, and interfaces module-to-module and interfaces with external systems. Functions and interfaces are intentionally defined to be common so a specific module can be used, interchangeably, at multiple places within the power system.[2] To complete the modular approach, a common means of electrically, digitally, and mechanically integrating the modules into scalable units is defined.

B. Modular Power Attributes and Capabilities

Required capabilities, such as, Reliability, Power Quality, Fault Management and Health Management are applicable to modular as they are to conventional non-modular power systems. The building block nature of modular power may require alternate means of achieving these capabilities. For example, fault and health management features may be built into the modules. Automated electronic integration and configuration or so called Plug and Play features are emphasized for Modular Power. Methods of uniquely identifying modules are needed to assure proper configuration control and to link health and fault management with specific modules.

The following are the attributes and capabilities of modular power. They are driving requirements in the development of modular power standards. These are interrelated and together these attributes assure a high level of capability. These attributes and capabilities distinguish Modular Power from non-modular architectures.

1. Commonality

"Commonality" implies that the hardware shares a common physical, data and electrical form and format. Commonality is intended to allow spacecraft share a common set of spares and allow interchangeability. The common building block approach is particularly applicable to multiple vehicles that a part of the same mission.

2. Flexibility, Scalability

"Flexibility" attribute assures that spacecraft power systems can be built to meet varied spacecraft needs from a common set of building blocks that can be arranged into a variety of configurations. This extends to scalability where the modular approach enables the system to scale capacity up or down incrementally.

3. Configurability (Automated Configuration and Integration)

Changing the configuration of a system to meet changing mission needs can be time consuming and prone to integration problems. Configurability must be attended with automated means of tracking configurations and automating the integration process. Therefore, hardware changes are supported by "plug and play" capabilities that automatically address configurations changes. A recently published AIAA standard AIAA G-133-1-2013 Space Plug-and-Play Architecture, outlines a number of concepts that support rapid integration of hardware and software. They include, component (module) detection, registration, self-identification, command and response messaging, publish and subscribe messaging and system monitoring and (module) status[3]. The features required to support these functions are manifested as embedded firmware and embedded data or "*electronic data sheets*" that are stored in module memory and accessible by the network.

4. Interoperability

Interoperability, primarily applies to data systems that must interact even though their internal data architectures are different. Data system interoperability is achieved by utilizing a standardized data exchange protocol and data formats. For power, it implies that hardware can be configured or adjusted to be compatible and capable of working together as part of an overall power system. This implies that modules share a common set of electrical and data system standards that allow them to interoperate with minimum integration effort.

5. Supportability

Supportability involves in-space maintenance, spares logistics, in-space operations and ground support that contribute to the *cost of supporting* flight operations. Modular power hardware will incorporate "*supportability*" features that enable systems to be maintained with minimum tools and equipment, minimize the mass of spares, while further minimizing crew time and dependency on ground support for logistics. Designing for supportability involves features that provide easy access to hardware and allows replacement with minimum level of disassembly and violation of system integrity. Since much of the time expended in maintenance involves isolating and diagnosing the root cause of problems, supportability is improved when hardware provides robust self-diagnostics. Supportability is further improved when unit life is extended and spares consumption is minimized by using health management techniques. When hardware is replaced, automated integration and configuration help minimize the effort required to integrate modular hardware. Supportability features that reduce maintenance also enable modular power hardware to be moved from one location to another or from spacecraft to spacecraft with a minimum level of effort and thus improving system flexibility.[4,5]

6. Availability

Availability takes into account that complex spacecraft systems are never 100% reliable and degrade over time. The time that the system is out of service due to loss of function and the time required for maintenance reduces availability. The modular approach improves availability because supportability features reduces the time to replace faulty hardware and quickly restore full function.

C. Example of the Modular Approach

A modular power architecture distributes power in the conventional way where main bus power is channeled to Power Distribution Units (PDU) that, in turn, distribute power to individual electrical loads. Each load is switched independently to isolate the loads from the rest of the system in the event of a current fault. Normally, the switching elements are sized for the required current. Switching units are differentiated by capacity and thus there is not a single common interchangeable unit.

In contrast, the modular approach to PDU design emphasizes *Commonality* by defining a common switching module utilizing a set of common switching devices that serve as building blocks. To address the need *Flexibility and Scalability,* the PDU switching modules are designed with *Configurability (*Automated Configuration and Integration*)* features that allow them to be combined together as a single "*power channel*". This is an example of how the Modular Power Standard achieves the desired modular commonality while still providing scalable power.

D. Organization of the Modular Power Standard

The overall modular power standard addresses the modularity at multiple levels and this is organized as illustrated in Figure II-1. The top level document deals with the overall modular power design philosophy. *Modular unit standards* are the 2nd level documents that define how the design philosophy is applied to major functions performed by assembly level units. This 2nd level is composed of a set of functional and interface requirements with special emphasis on commonality.

Examples of designs that meet the functional and interface requirements represent 3rd level documents. These documents are expected to be appendices to the 2nd level. Specifications used in the examples should be consistent with the 2nd level requirements. The example cases of the 3rd level will have electrical interfaces are defined down to the pin level. Details of the backplane and the thermal and structural design are included. The 3rd level is intended to provide design guidance and illustrate both the benefits and limitations of a specific solution to modular power.

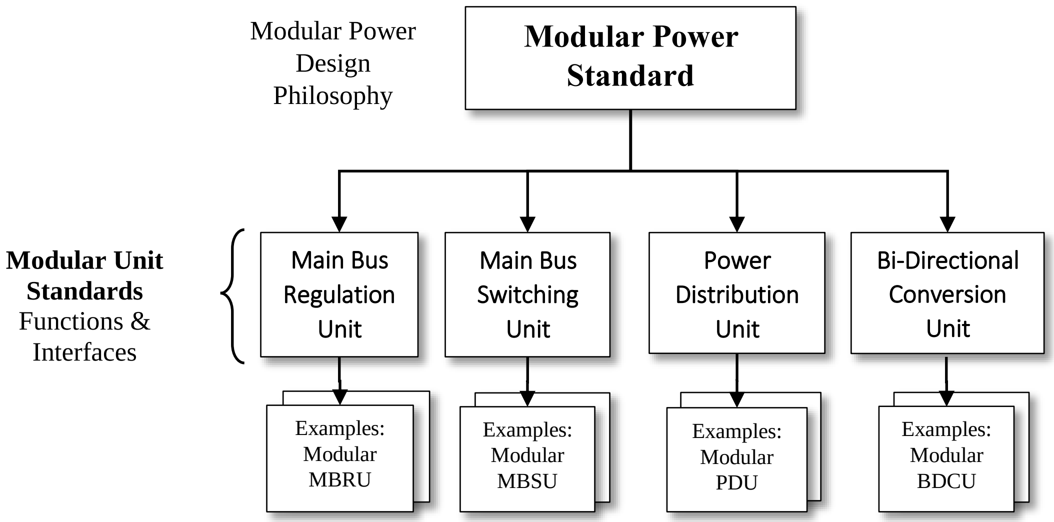

Figure II-1: Modular Power Standards

III. Modular Power Distribution Architecture

The illustration in Figure III-1 shows a generic modular assembly level unit typical of an Orbital Replacement Unit. The unit is composed of modules that perform specific functions attached to a supporting backplane. The use of a common backplane populated by modules that provide commonly used functions is used throughout the Modular Power Distribution Architecture. The term Orbital Replacement Unit, therefore, now applies to subassembly level modules.

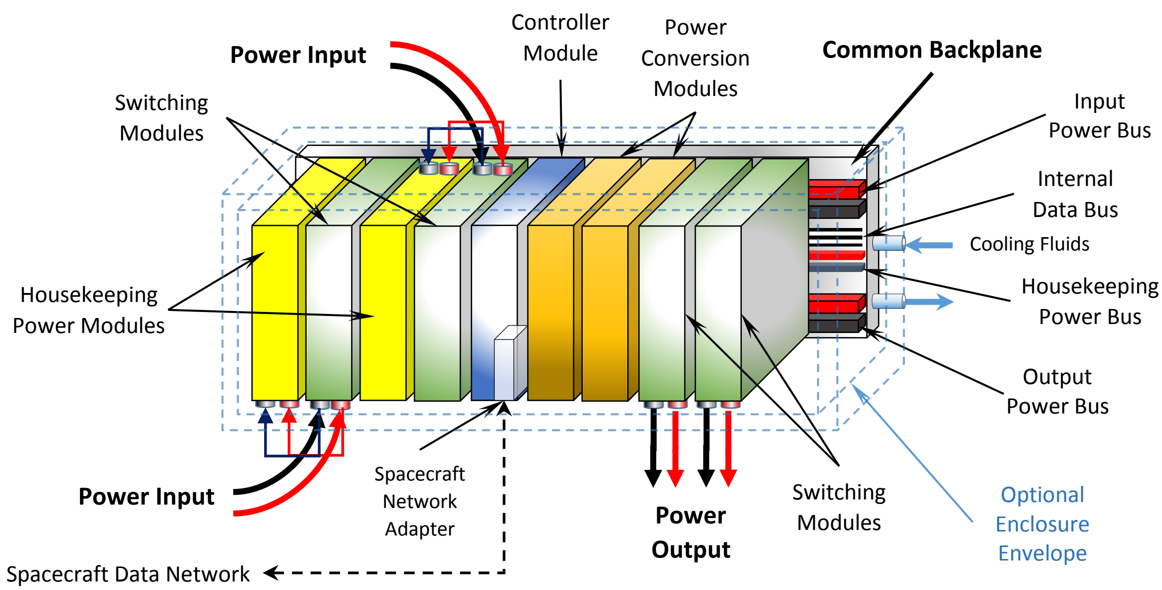

Figure III-1. Generic Modular Power Unit. This generic assembly shows several functional modules that are interconnected with a common backplane to form an assembly level unit.

A. Modules Supported by a Common Backplane

The backplane supports interfaces that are common and available to all the attached modules. Figure III-1 shows a simplified backplane that provides a minimum of three busses. Note that the common backplane does not require that the modules take pre-assigned positions. The modules can access all the backplane buses from any location on the backplane. Many unit level assemblies may require a *fourth bus* to support an alternate voltage level, or support converter module outputs. Units that have power converters or bus regulators can use this additional backplane power bus to handle input power and output power on the same common backplane.

In Figure III-1, the modular assembly would perform all the functions of an equivalent assembly level ORU but the replaceable hardware now occurs at a lower level of assembly. A single planar backplane is an ideal example that provides the greatest possible access and allows the greatest flexibility for locating external interconnections. A similar approach is used by industrial equipment manufactures to provide design flexibility, accommodate configuration changes, and upgrades as user needs change.

The backplane in Figure III-1 also shows an interface with the spacecraft fluid thermal control system. In this illustration, all mechanical interfaces (structural and thermal) are provided by the backplane. The backplane may use alternate cooling methods such as a cold plate or radiator. The backplane may be designed to serve as the primary structural and thermal interface with spacecraft systems as shown in Figure III-1. The modular unit standards require that the backplane and any attending structure meet the thermal requirements defined by each module.

If required, an enclosure may be used to provide further support of both the thermal control and structural dynamics needs. The exact spacecraft thermal and structural dynamic environment depends on the mission requirements. Since these requirements vary from spacecraft to spacecraft the explicit spacecraft thermal and structural requirements are not addressed in the standard. Specific mechanical specifications and design solutions are covered in the Examples Appendix of each Modular Unit Standard.

Spacecraft designers are encouraged to consider that modules are encapsulated to be physically robust. The modules provide the first layer of thermal control and structural support and thus more massive than simple circuit cards. The mass penalties of encapsulating sub-assemblies into modules can be minimized if the backplane or enclosure is designed to account for the rigidity that the modules contribute to the overall structure, and the internal heat conduction that individual module walls provide.

B. Modularized Power Distribution Architecture

Figure III-2 illustrates a modular power distribution architecture where major assembly level units or Orbital Replacement Units are replaced by backplanes that support an array of functional modules. Note that although these units provide different power distribution functions they share certain internal functions such as a unit (backplane) controller, input and output switching, and housekeeping power. These, in turn, are performed by a common set of modules. The power switching and conversion functions can exploit building block approach to scale the unit's power handling capacity.

C. Power Converters and Regulators

Figure III-2 shows a Main Bus Regulator and Bi-Directional Converter. Both use a set of regulator modules under the control on a common backplane controller. In low power situations, the controller deactivates some modules to increase efficiency. This is an example of how the modular system can actively scale itself to match the needs. When demand increases the addition modules are activated. Regulators communicate load sharing information through the backplane data bus. The Unit Controller coordinates the regulators so they properly share the power load.

D. Main Bus Switching

The Main Bus Switching Unit acts as a central switching hub for main bus power. The MBSU connects the main bus power to Regulated Array Sources, Batteries, and External Power from other spacecraft. The main bus power is then distributed by individually switched output modules. Each main bus channel will provide power to individual Power Distribution Units that in turn distributes power to loads. The coordination of input and output switch configurations is handled by the spacecraft Automated Power Controller software the MBSU Unit Controller handles the switching commands. Depending on the architecture, the MBSU may require multiple internal busses to assure that inputs and outputs remain separate if bi-directional power or energy storage are connected.

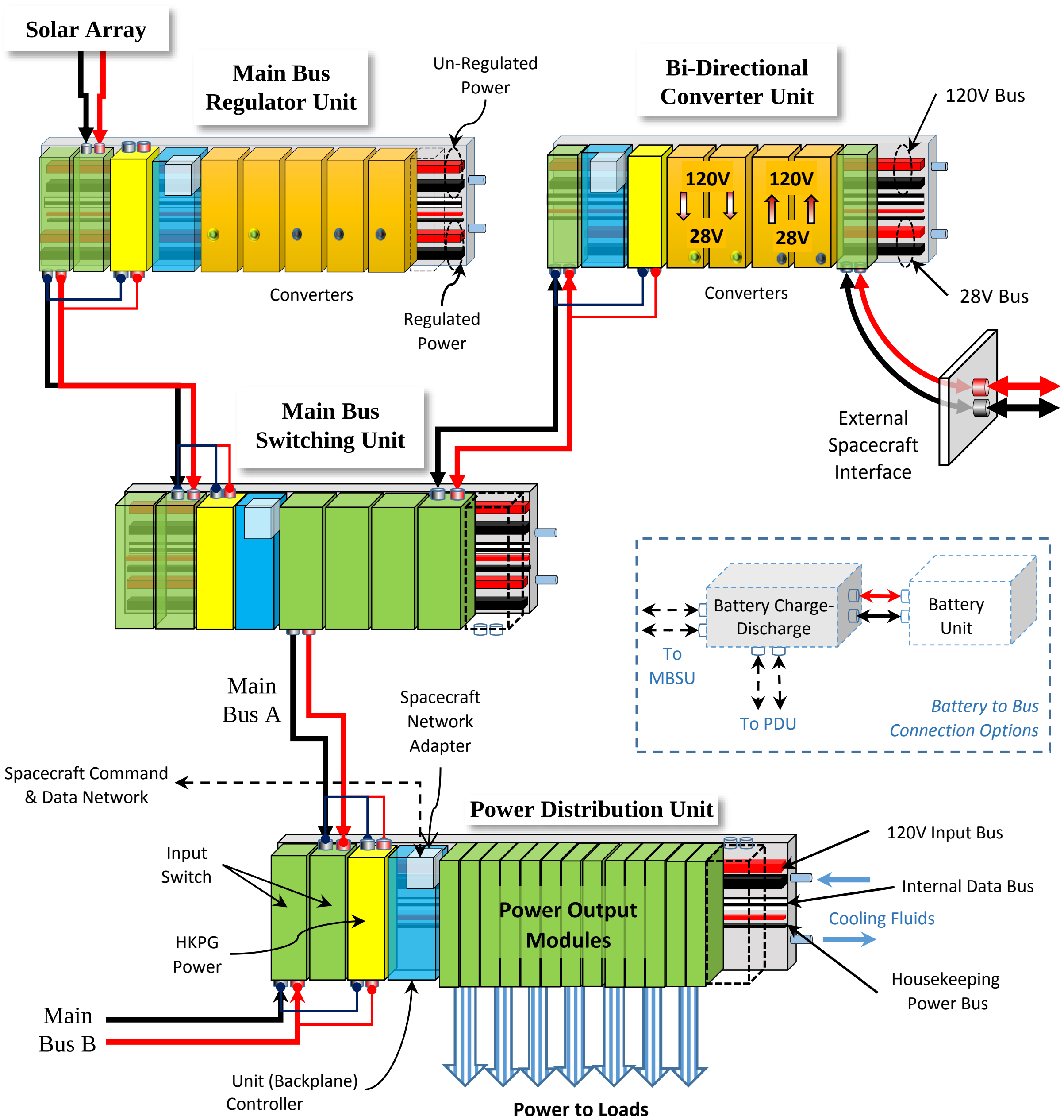

Figure III-2. Modular Power Distribution System. The power architecture is composed of assemblies or modular power units built from a common set of modular building blocks and common backplanes.

E. Power Distribution Unit (PDU)

The Power Distribution Unit acts as main interface between spacecraft loads and the power system. It distributes main bus power as dedicated power channels. Each channel has load fault protection that protects the main bus from local current faults. Each channel is composed of one or more remote power controllers (RPC) that function as both a power switching element and a fault isolation device. The PDU may have access to multiple main busses and may switch from one bus to another in the event that a bus is failing or to allow an automatic power control system to redistribute power as mission needs and power availability change.

F. Battery and Charge-Discharge Unit

The modularization of charge and discharge control is still evolving. There are new battery safety engineering standards that will affect how the batteries and related charge and discharge regulation will be modularized. Much depends on the approach to energy storage. Energy may be stored in a central location or distributed at key points in the distribution system. The charge-discharge function may take the form of a stand-alone modular assembly with its own backplane and handling multiple batteries. Alternatively, the charge-discharge function may take the form of plug-in modules to be installed into a Main Bus or Power Distribution unit and supporting a single battery.

IV. Automatic Power Control and Management

The Automatic Power Control (APC) is software that may reside in a dedicated controller or as a software module within the spacecraft flight computer. The spacecraft APC is not explicitly part of the Modular Power Standard. However the standard does define functions and capabilities that the APC software will be expected to perform in support of the modular approach. The APC manages the overall power system which includes Power Generation, Energy Storage, and Power Distribution. The APC handles allocation of power, determines which main bus that will be utilized by specific power distribution units and determines which loads are to be powered in nominal and off nominal situations. The APC manages the power distribution through communications with unit controller modules found in each modular power units.

A. Unit Controller Communications

Modular power hardware is required to support the automated configuration processes that the APC software uses to manage the overall power system configurations. Each unit level assembly has a dedicated *Unit Controller Module*. The unit controller modules are expected to be interchangeable but can be specially configured for the specific unit. The unit controllers act as remote terminals for the spacecraft data system and handle all communications traffic between the spacecraft and the modular power unit. Each unit has a programmable *Spacecraft Networked Adapter* that is “slaved” to the Unit Controller and designed to adapt to the spacecraft network regardless of the protocols used.

Every module attached to the backplane is required to communicate via the Internal Data Bus. The Unit Controller also serves as the unit’s *local backplane bus master* and manages the Internal Data Bus.

B. Automated Integration and Configuration

Because many of the modules are intentionally designed to be common and generic, it is important that the power modules provide unique embedded identities (such as serialized IDs) and unique addresses for specifying module locations. Each unit must accept, store and utilize unique identifiers assigned by the spacecraft level APC software. The APCs power system configuration data base is built around these unique identifiers. Commands and status data is routed through the network using these identifiers.

Whenever a unit is replaced or added to an assembly the unit level controller will recognized the module change and coordinate with the APC to update the power system configuration. The identifiers and location addresses registered in the APC data base will be updated, as needed, to integrate the new hardware into the system.

C. Fault Management

The Fault Management is responsible for reacting to faults and unanticipated changes in the system. Power faults are isolated using dedicated devices that act to isolate a fault and prevent it from propagating into a system wide failure. However, power system fault isolation such as a RPC Trip (opened circuit) does not address the consequence of the loss of function that may result. Spacecraft Fault Management is a Cross System Software that is intended to monitor for faults and react by taking steps to “*Safe the System*” when faults occur. Fault management utilizes pre-programmed and pre-tested algorithms that provide timely response to anticipated faults. They are triggered by non-ambiguous messages or “event status flags”. These flags may actually indicate a complex situation and may require a complex response but the status message is intentionally kept short so it is transmitted quickly and checked frequently. Individual power modules report status to the unit controller and in-turn, the unit controller reports the status to the Fault Management system via the spacecraft network.

D. Health Management

Health management is less reactive than fault management and is intended to detect problems and analyze measurement data for indications that a problem may be arising that leads to a significant fault or possibly a catastrophic situation. Health management is intended to predict the onset of a fault and alert the crew or automated system manager to take action or change the configuration that could preempt the occurrence of a fault. For example, health management may detect a module temperature trend that indicates an eventual failure. In this case, a "Caution or Warning" message is sent to alert the crew to replace the faulty unit.

Health management also addresses ambiguities that arise when sensors do not agree due to a sensor failure. The Sensor Data Qualification function within Health Management may utilize test algorithms to determine which sensor is faulty and may then "disqualify a sensor" so that the Fault Management can ignore the faulty sensor and thus prevent a false positive reaction.

Individual power modules report health measurement data to the unit level controller. In turn, the controller reports the data to the Spacecraft Health Management system. Some health management functions, such as module self-diagnostics can be performed by unit level controllers and results periodically reported to Health Management. Alternatively, diagnostics routines may be triggered on command by a fault management or a health management algorithm.

V. Modular Power Distribution Unit Standard

The Modular Power Distribution Unit (PDU) Standard document serves as a template for the development of modular units defined by the overall Modular Power Standard. The Modular PDU Standard that can be regarded as a second level document under the Modular Power Standard. Similar volumes will be written for other unit level assemblies. The Modular PDU document is developed like a Functional Requirements Document where specific functions, interfaces, and interactions with other systems are specified. The requirements are intended to provide design guidance without explicitly designing the hardware. Many existing standards and specifications are used. To assure commonality it is important to utilize common modules that can be used elsewhere in the system. Each unit level assembly, however, has one or more unique modules that support the unit's primary function.

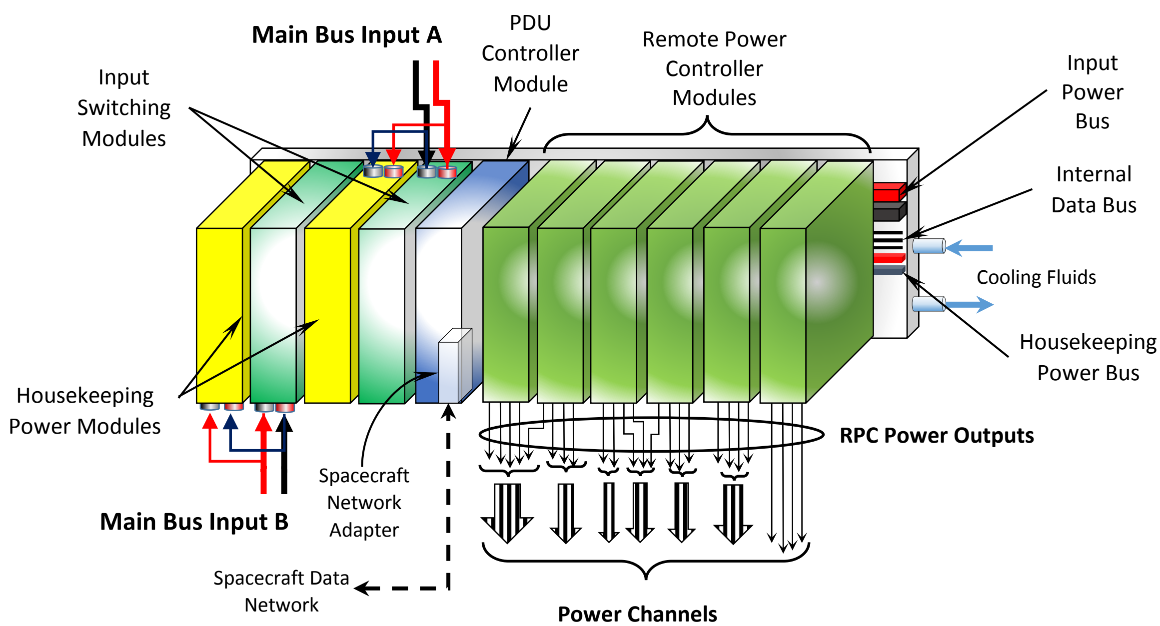

Figure V-1. Modular Power Distribution Unit.

A. Modular PDU Common Backplane

The PDU backplane provides an Input Power Bus that supplies Main Bus Power, a low voltage Housekeeping Power Bus that supports all modules, and an Internal Data Bus that provides communications to all the modules. The modules can access all the backplane buses from any location on the backplane. The Modular PDU relies on four module types; a PDU Controller, a Input Switching Module, a Housekeeping Power Module, and a Remote Power

Controller Module (RPC Module). The first three modules are common to other assemblies in the power architecture. Without the modules the backplanes are completely passive. Each of the common modules governs the one of the backplane busses and the capability of the bus. Multiple modules can be used to expand PDU capacity. Further, multiple modules may also be used if redundancy is required.

Figure V-2 is intended to show which modules govern the individual busses on the backplane. Note that there are no direct connections between the common backplane buses and the external systems. The modules act as the main interface with external systems. This preserves the commonality of the backplane.

In the example illustrated in Figure V-2, the three common modules are shown as redundant pairs. The input switching selects one of two main buses to power the input power bus. Housekeeping power is dependent on external bus sources so Housekeeping Power Modules use connections to each main bus to assure the all modules receive housekeeping power even if no inputs are selected.

The PDU Controller Module is a digital unit controller that handles both internal and external data communications. Using a spacecraft network adapter the PDU Controller acts as a remote terminal for the spacecraft data network. It also acts as an internal (backplane) data bus master. Depending on the application, redundant PDU controllers may be used. To accommodate redundant communications the backplane internal data bus will utilize redundant data paths and employ a data bus protocol that allows multiple masters to share the bus. If a single PDU Controller is used it will utilize a redundant connections on both external and internal data busses.

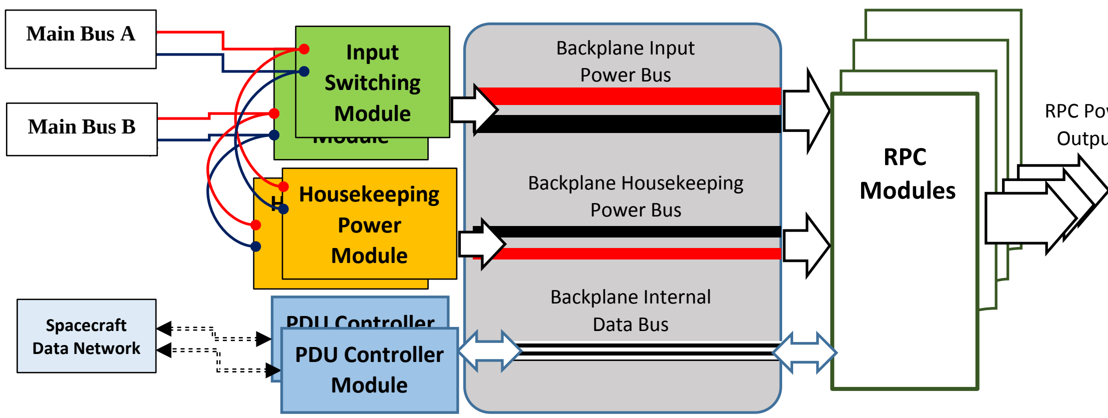

Figure V-2. PDU Modules Control Backplane Bus. The characteristics of each backplane bus is governed by specific modules**.** These modules serve as the interface between the internal bus and external systems.

The Remote Power Control Module is unique to the PDU. It connects to all of the backplane busses. The RPC Modules provide power output to individual spacecraft loads and thus does not directly share a common conductor for outputs. The grouping of RPC outputs into channels actually occurs off the common backplane and thus not shown in Figure V-2.

To assure flexibility and commonality the backplane will be populated with connectors that support all the common busses. Although each module will not utilize every connection they must be equipped with mating connectors that are compatible and allow modules to be placed in any available slot. The connectors also provide a means of identifying the specific location on the backplane. Each module can report its physical address by testing its connection to the common backplane. Each slot location has dedicated connector pin pattern that establish a unique address for each module.

B. PDU Controller Module

The PDU Controller supports many common and unit specific functions. It is expected to feature a powerful microcontroller and field programmable devices that will enable it to provide unit level control of modular power units throughout the architecture. Below are the main functions it provides for a Modular PDU.

1. PDU Controller Communication Functions

The spacecraft flight computers utilize a dedicated Automated Power Control software to manage the configurations of the individual PDUs. The PDU Controller serves the digital controller for the PDU and responds to APC commands and reports status and measurement data to the APC. The spacecraft APC determines which main bus that the PDU will utilize and determines which loads are to be powered in nominal and off nominal situations. The PDU Controller manages all the other modules and passes commands to each module and gathers status and measurement information from the modules. The PDU Controller also reports predefined set of status and measurement data to the APC. The PDU controller also reports fault status that can be used by the APC Fault Management.

The PDU Controller connects to the spacecraft network via a Spacecraft Network Adapter or SNA. The SNA may be an add-on module specifically designed to serve as an adapter. Alternatively, PDU Controller may be capable of synthesizing a SNA interface with software and field programmable logic gates.

Generally, PDUs will continue to provide power to critical systems even when communications with the flight computers and APC is lost. This way a loss of PDU communications does not propagate to a loss of spacecraft power. However, loss of comm means that the APC no longer has control of the power system. This illustrates the need for PDU Controllers with redundant communications.

2. PDU Controller Start-Up Functions

Generally, start-up of the PDU requires that the PDU Controller completes its initialization before any other modules (except the Housekeeping Power) are activated. That means, that the PDU Controller must be fully ready before power input switching occurs and before any power outputs are enabled. Assuming the Flight Computers are functional and the network is available, the PDU Controller will establish communications with the network. The controller will then and send a “PDU Ready” signal to the flight computers and await input switching and output power up sequence commands.

In a case of a *cold start-up*, where there is no Flight Computer or Network because they are unpowered a predefined start sequence is executed where default inputs are selected and predefined outputs are enabled to allow the data system to come up in an orderly fashion. The PDU then waits for the spacecraft network to initialize and looks for the “*Flight Computer Ready”* signal to establish communications with the network. Once confirmed, the PDU awaits commands to complete the power-up sequence and switches power to other spacecraft systems. Because there may be many PDUs distributed across the spacecraft, the each PDU will need a unique *cold start configuration*. Controller internal software will need to detect if a true cold start condition exists before executing the preconfigured routine.

3. PDU Controller Shut-Down Functions

There are a number of nominal and off-nominal situations where the parts of the power system will need to be shut down. As long as the data network is functional the PDU can shut off individual loads in an orderly fashion by commanding RPCs to go to the “Open” state. All the loads can be turned OFF but the PDU Controller and attached modules can still function as long as there is a main bus power available. If a shutdown of a main bus is planned then the PDU Controller *can be configured for the next start-up sequence prior to* the shutdown. The sequence must be stored in the PDU Controller’s *non-volatile memory* so that it can recall the sequence upon power up. This is particularly true if a cold-start is anticipated so the PDU Controller can act independently of the network and flight computers for the subsequent restart.

4. PDU Controller Internal Data Bus Management

As noted earlier, the PDU Controller acts as the “Bus Master” and controls the behavior of the data bus. The specific means of identifying units, assigning priorities, and resolving bus contention is governed by the specifications of data bus protocol. The Internal Data Bus need not have the same architecture as the spacecraft data bus. However the internal data bus must be common across all the modular power units that use the common backplane. The PDU Controller must support the internal data bus redundancy protocols and communication standards. If a single PDU controller is used then redundant bus transceivers and redundant bus controllers are required.

5. PDU Controller Module Commands and Data

The PDU Controller receives commands and acts on them directly or translates them into internal commands to be issued to specifically addressed modules via the backplane Internal Date Bus. The PDU Controller relies on other modules to provide sensor data acquisition and detect switch states. Information, such as, power input voltage and current, output power parameters, switch states, fault status, and module temperatures are all provided by other modules. PDU status and measurement data collected is then processed by the PDU Controller and transmitted to the spacecraft APC via the spacecraft data network.

6. PDU Controller Module Automated Configuration

To exploit the flexibility of the modular approach requires an emphasis on dynamic configuration control. The APC software, the Modular PDU and the individual modules must incorporate features that make is easy to automate the process of locating and identifying individual modules. The ability to assign unique IDs and track devices is essential to support automated integration and configuration (Plug and Play), fault management and health management functions. This is particularly useful when hardware is replaced due to maintenance or the system is reconfigured to meet changing mission needs.

The PDU controller must establish unique identities and the location addresses of each module on the common backplane. Modules with internally addressable devices such as the RPC devices within the RPC Modules will have additional address and IDs assigned.

Each module on the common backplane can report its physical address by testing the unique address pins found in each backplane connector. Each slot location is matched with the module's permanent internally stored serial number. This address and identifier are assigned a unique system ID, that includes the PDU ID, and is *registered* by both the PDU Controller and the APC system. That means any module in the power system, attached to a backplane, can be located and receive commands from the APC.

C. Input Switching Module

1. Input Switching Functions

Input Switching is a very simple module that contains switching elements capable of handling the high current that is powering the PDU. The Input Switching Modules provide an overcurrent trip to protect the main bus from an internal current fault. It also provides an overvoltage trip that protects the loads and internal modules from excessive input voltage.

The module provides switch status along with voltage, current and temperature data. This information is reported to the PDU Controller using a simple microcontroller and an internal data bus interface. The state of each attached main bus is monitored so that the PDU Controller can know which busses are powered. This helps prevent the PDU from inadvertently switching to a main bus that has inadequate power. The module can report its location on the backplane and its serial number. Further, it can store an assigned unique identifier so that it can respond directly to commands issued by the APC.

2. Input Switching Start-up and Shut-down

The Input Switching Module is used in the start-up sequence but does not act independently. Since it is a single switch, it only represents part of an input power selection function. The use of individual switching modules rather than an integrated channel selector allows the number of inputs to be varied from PDU to PDU. Thus a PDU can be configured to select from two or more inputs using a common module. All Switching is controlled by the PDU Controller. The Input Power Switch Module requires Housekeeping Power to be activated. If all the main buses drop out, the input switches open and this assures that the PDU restarts with switches in a safe state upon reapplication of power.

D. Housekeeping Power Module

1. Housekeeping Power Functions

The Housekeeping Power Module serves as power supply that converts main bus voltage (120 VDC) to a low (5 VDC) voltage that is, in turn, supplied to the Housekeeping Power Bus. It provides power to all the modules attached to the common backplane. The module reports Housekeeping Power Bus status and measurements to the PDU Controller. Like other modules, it can report its location address, accept and store assigned unique identifiers and respond to commands and using the Internal Data Bus.

The Housekeeping Module has an isolated DC/DC converter that protects the main bus on the input side from faults on the output side. The converter is designed to drop the output bus to 0Volts in the event of a backplane bus fault. The voltage returns to normal when the fault is cleared.

2. Start-up and Shut-down

The Housekeeping Power Module uses a connection to the Main Bus that bypasses the Input Switching Module so that it is the first to react to the application of power to the Main Bus. Once stabilized, it applies current to the Housekeeping Power Bus and allows the rest of the modules to power up. It starts reporting status and measurement data once the Internal Data Bus is initialized by the PDU Controller. The Housekeeping Module does not have ON/OFF switch because it is hardwired to power up once a main bus is activated. To turn Housekeeping Power OFF is accomplished by opening the contacts at the Main Bus Switching Unit.

E. Remote Power Controller (RPC) Module

Remote Power Controller Modules provide the main power distribution function of the PDU. They are the primary interface between the power system and the spacecraft loads. They provide power switching and provide power fault isolation to protect the main bus and other channels from localized current faults.

1. RPC Module Power Switching Functions

The four RPC devices in the RPC Module provides basic DC current switching to user loads. RPCs can be commanded ON, OFF, and RESET. The RESET is needed only after an overcurrent condition triggers a "Trip" and the circuit opens. When a trip occurs the system will still indicate that it is in the ON state even though the circuit is physically open. To clear the inconsistency between the commanded state and the physical state an external RESET command is issued that clears the TRIP state and cycles the RPC back to an ON state. This assumes that action has been taken to assure that the fault that triggered the trip has been cleared.

2. RPC Module Overcurrent Trip, and Current Limiting Functions

The RPC Trip function responds to an overcurrent condition by opening the circuit to isolate the fault. RPC protects the main bus from the resulting voltage drop that would otherwise disrupt power to adjacent power channels. There is a delay in the RPC TRIP where the delay is affected by the severity of the overcurrent. During the delay period the RPC Current Limiting function activates and restricts the current to within 110% to 120% of the specified limit. Current Limiting delay of the TRIP is constrained by the severity of the overcurrent where the more severe the condition the shorter the time before the RPC trips. For minimum overcurrent conditions, for example 110%, the overcurrent condition may be tolerated indefinitely. This helps desensitize the RPC from short transients and minimizes the incidents of nuisance trips. Current limiting also improves the power quality by minimizing the effect of current transients on bus stability.[6]

3. RPC Module Configuration and Data Functions

The RPC Module is composed of four individual RPC devices. Each module can report its location on the backplane and its internal serial number. Further, each RPC device has a unique identifier and address within the module. Each module can store the unique identifier assigned by the APC system and use it for receiving commands and reporting status.

These identifiers are essential for allowing the PDU to create *RPC Power Channels* that are composed of multiple RPCs. The APC and PDU Controllers determine which RPCs make up the channel group. When RPC Power Channel commands are received, the PDU controller re-issues individual RPC Commands simultaneously. Likewise, the RPCs reports individual power measurements to the PDU Controller that, in turn, reports composite readings of the RPC Power Channel.

4. RPC Module Start-up and Shut-down Functions

Generally, once the PDU has gone through a start-up cycle the PDU Controller starts activating the RPC outputs.
If main power has been cutoff the RPC devices automatically go to an "Open" state. At startup they are in a default "Open" state must be commanded to a "Closed" state by the PDU Controller.

5. RPC Module Loss of Comm Condition

Preserving power is essential, so the design must assure that power flows even when communications is lost. If the Modular PDU Controller were to lose communications with the network the PDU maintains the last commanded RPC state. This also applies if the loss of communications occurs on the internal data bus. Therefore, a *loss of communications* with a PDU does not result in a *loss of power*.

VI. Modular PDU RPC Power Channels

A. Definition of RPC Power Channels

In conventional Power Distribution Unit the RPCs distribute power to individual electrical loads. Normally, each RPC is sized to match the required current load. This means the PDU is populated by a family of the switching devices that are only interchangeable with units of similar size. This limitation on commonality limits flexibility and requires that a mission carry the weight penalty of maintaining a diverse set of RPC spares.

Using a common building block approach it is possible to arrange common sized RPC modules in a manner that is scalable. The Modular PDU uses relatively small RPCs and provides a means of combining their capacity into a single output that we define as a "RPC Power Channel". The RPC Power Channel can involve any number of available RPCs. The RPC Channels can also span multiple RPC modules. RPC Channels based on a common sized RPC improves supportability by utilizing a common set of spares. The spare can be are shared with other spacecraft and thus minimizes the total mass of spares for the mission.

B. RPC Power Channel Formation

The physical wiring of the RPCs and the RPC Power Channel Configuration define how a Power Channel is formed. Physically the RPCs are hardwired to a single load. The number of physical connections is based on the load's power requirements. As illustrated in Figure VI-1, the physical connection may span multiple RPC Modules. In most cases, the adjacent RPCs and adjacent modules will be used. Within the constraints of the physical wiring, the PDU Controller can adjust the channel member assignments to match the power requirement. Based on channel configuration data provided by the APC the PDU Controller establishes the configuration of the group by using the identity and location of each of the members of the channel.

The current concept assumes 5 Amps of nominal current capacity per RPC. With four RPC devices in each module, each RPC Module has a total of 20 Amps of capacity. Therefore, a load of 45 amps, for example, would utilize 9 channels that are distributed over two RPC modules plus one additional device from a third module. This is illustrated in Figure VI-1.

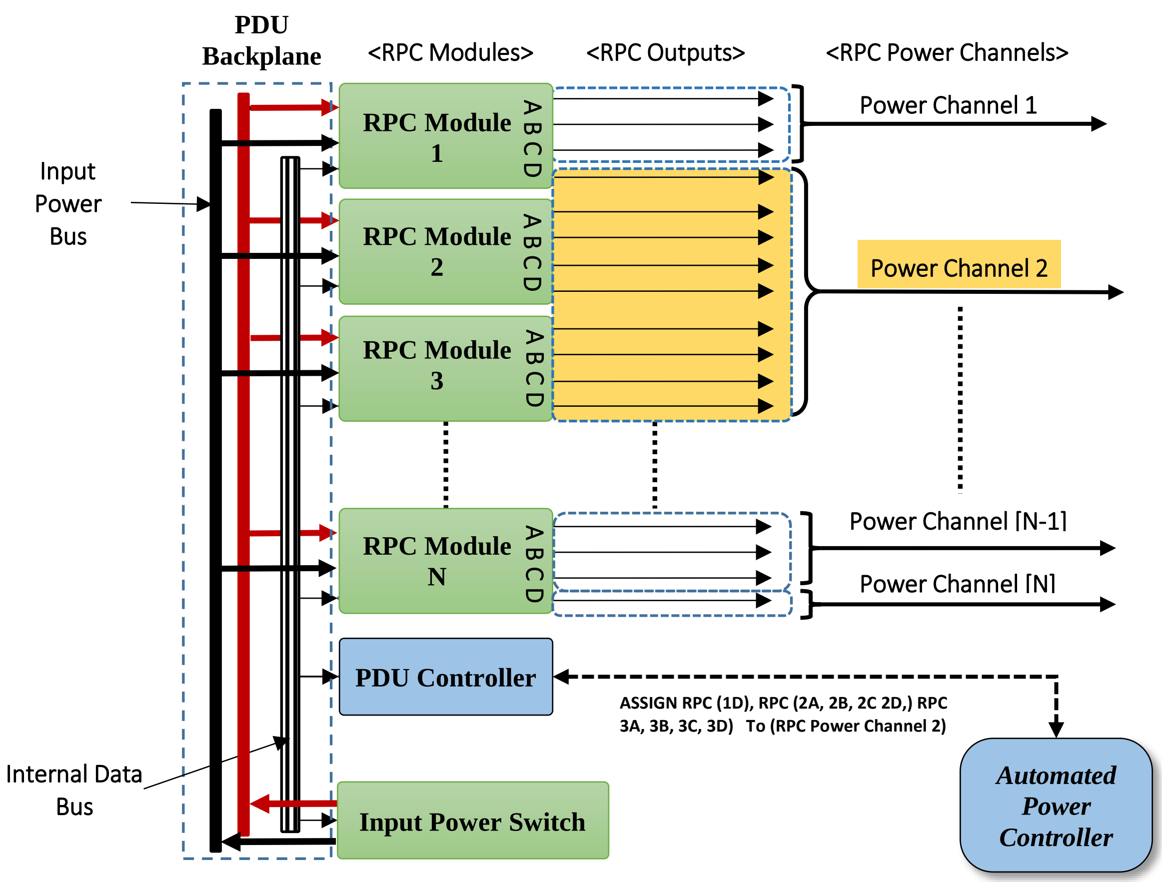

Figure VI-1. RPC Channelization Diagram. The APC sends channel assignment commands to PDU Controller to group individual RPC Outputs and form a RPC Power Channel. A RPC Power Channel may span multiple RPC Modules.

C. Coordinating RPC Identity and Location Addresses

To manage the channelization of RPC outputs the PDU ID, the RPC Module IDs, RPC IDs and Module Physical Address is sent to the APC. Using a data base that maps the wiring connection of PDU outputs to their assigned loads the APC correlates the each load to a RPC Channel that may have one or more RPCs. The RPC Channel gets unique ID and the specific RPCs are assigned to it. The channel configuration is sent to the PDU Controller that uses it disseminate the *channel commands* to the specific RPCs in the group. The APC can now interact with the RPC Power Channel as if it was single RPC device.

D. RPC Power Channel Fault Protection

Modular RPC Power Channels fault protection relies on the individual RPC devices fault protection. Fault protection is hardwired and cannot be commanded. Fault protection circuits involve analog devices that tend to have slight variations from unit to unit. Further, the actual current on each of the parallel wires will see slight variations in conductor and contact resistance. Therefore, when an overcurrent condition occurs the RPCs will not trip simultaneously. Instead we should expect one device to lead the others.

The first unit that responds to an overcurrent condition goes into a current limiting mode before it trips. Current limiting will cause the remaining RPCs to experience a higher share of the load and in turn go to current limiting. The overcurrent becomes progressively more severe for each remaining RPC. As RPCs trip the current limiting time delay will become progressively shorter and hasten their trip action. The more RPCs that trip the faster the remaining units will trip. Therefore, RPC trip function should operate in parallel with no special coordination.

At start-up, the switching of RPC Channel devices must be closely coordinated by the PDU Controller so that all RPCs pick up their share of the load simultaneously. If there is significant lag between RPCs then the first to close will see excessive current loads and may trip before the other units pick up their share of the load. Activating multiple RPCs within the RPC Channels must meet predefined timing requirements to assure a trouble free start up.

VII. Conclusion

At NASA Glenn Research Center, a modular approach to spacecraft power has been evolving under the AMPS project and a set of draft Modular Power Standards continues to evolve. The Modular Power Standard establishes the modular power philosophy involving a *common building block* approach can provide flexibility and scalability while improving supportability of exploration missions. A Modular Power Standard applies the philosophy to the design of unit level assemblies so that they are now composed of a set of common replaceable sub-assembly level modules.

The standard describes modules that support common roles such as input switching, housekeeping power, and unit controllers that can be used throughout the power architecture. The standard also describes modules that provide specialized functions, such as, power switching and power regulation. These are standardized to act as power building blocks that can be combined to provide a scalable power capabilities. The Modular Power Standard also defines a common backplane that serves as a power and data backbone for integrating modules into an assembly level unit.

The flexibility and scalability of modular power involves more than physically encapsulating sub-assemblies. The ability to dynamically configure the power system to meet mission needs requires that both the Automated Power Control software, and the individual modules, incorporate features to support the automated integration and configuration. The individual modules must provide embedded software/firmware that allows the flight computers to alter their configuration. The spacecraft Automated Power Control software will utilize unique identifiers and addresses to track individual modules, manage configurations, and update fault and health status.

The Modular Power Distribution Unit Standard illustrates how design philosophy of the Modular Power Standard influences the design of modular units. Modular PDU internal functions are encapsulated as standardized modules that can be used throughout a power architecture. The Modular PDU ability to build RPC Power Channels from standardized RPC Modules illustrates the flexibility and scalability of the modular approach.

The Modular Power Standard is currently a draft document. The AMPS project will begin the formal process of review and comment that will eventually lead to a formal standard. If readers are interested in contributing to the standard's development, please contact the authors at NASA Glenn Research Center in Cleveland, Ohio.

VIII. Acknowledgements

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